

# Microlensing & Scintillation of Gravitationally Lensed Compact Radio Sources: Evidence for MACHOs?

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**Abstract.** We present the first unambiguous case of external variability of an extra-galactic radio source, the CLASS gravitational lens B1600+434, consisting of two images lensed by an edge-on disk galaxy. The VLA 8.5-GHz difference light curve of the lens images shows external variability at the  $14.6\text{-}\sigma$  confidence level. Although the current single-frequency VLA observations cannot conclusively exclude scintillation, several lines of evidence show that it does not dominate the short-term variability. This is supported by an ongoing three-frequency WSRT campaign. If scintillation is the dominant source of this external variability, it would require very different properties of the Galactic ionized ISM towards the two lens images. Microlensing of a superluminal jet component can explain both the rms and time-scale of variability, but requires the halo of the lens galaxy to be filled with  $\gtrsim 0.5\text{-}M_{\odot}$  MACHOs. The current data appears to support microlensing as the dominant source of the observed external variability.

## 1. Introduction

Gravitationally lensed compact radio sources have many astrophysical and cosmological applications, amongst which the determination of a time-delay to constrain the Hubble constant is best known (Refsdal 1964). Once a time-delay has been determined from the image light curves, they can be subtracted to see if any externally induced variability is present. External variability in compact radio sources can be the result of either scintillation by the Galactic ionized ISM (Rickett 1990) or microlensing by compact objects in the lens galaxy (Chang & Refsdal 1979). Unambiguous external variability thus offers the opportunity to study either the ionized medium towards the lens images or the mass function of compact objects in high- $z$  galaxies. Here, we discuss both possibilities as the source of the external variability observed in the CLASS gravitational lens B1600+434 (Koopmans & de Bruyn 1999 [KB99]).

## 2. Observations

B1600+434 was observed from February to October 1998 with the VLA at 8.5-GHz, in order to determine a time delay between the two lens images (Koop-

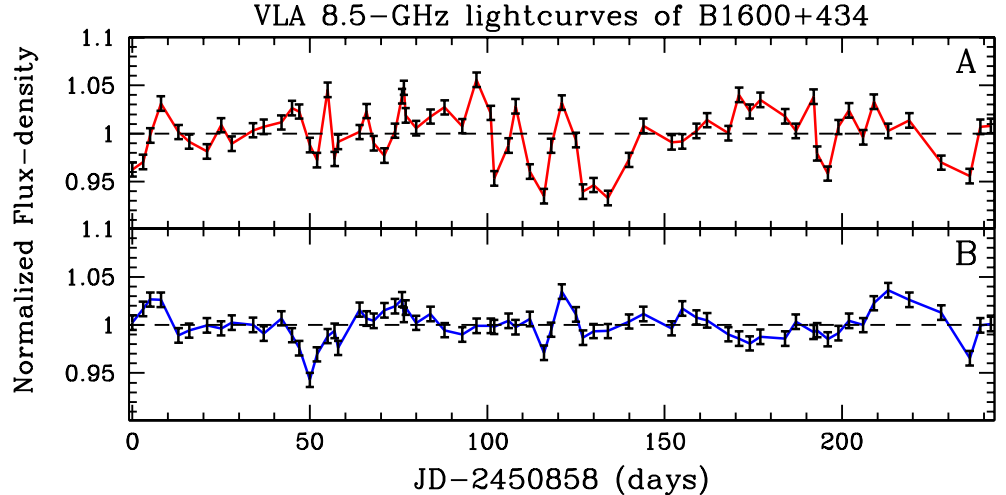


Figure 1. The normalized light curves of B1600+434 A (upper) and B (lower), corrected for a long-term gradient. The error on each light-curve epoch is 0.7 to 0.8% (KB99).

mans et al. 1999 [KBXF99]). In Fig.1, the normalized VLA 8.5-GHz light curves of both lens images are shown, created by subtracting a linear fit and subsequently normalizing them to unity (KBXF99). The resulting normalized light curves have rms variabilities of 2.8% and 1.6% for images A and B, respectively. Subsequently, the observed linearly-interpolated light curve of image B was subtracted from the light curve of image A, after having corrected it for a flux density ratio of 1.212 and a time delay of 47 days (KBXF99). The normalized difference light curve (Fig.2) has an rms variability of 3.2%, which is inconsistent with a flat difference light curve at the  $14.6\text{-}\sigma$  confidence level. A time delay different from 47 days only increases the confidence level, as a result of using a minimum-dispersion method to determine the time delay (KBXF99).

### 3. Analysis

Below we investigate both scintillation and microlensing, as possible causes of the external variability in the lens images of B1600+434. We regard extreme scattering (Fiedler 1987) as unlikely and will not further discuss it here. The reader is referred to KB99 for a full discussion of all the details.

#### 3.1. Scintillation

Scintillation, caused by the Galactic ionized ISM, can explain both large amplitude variability in very compact extra-galactic radio sources and lower amplitude ‘flicker’ of more extended sources (Rickett 1990). In B1600+434–A and B, we observe several percent rms variability, possibly consistent with ‘flickering’. The time scale is harder to quantify, but it appears that we see variability time scales of several days up to several weeks (Figs 1–2).

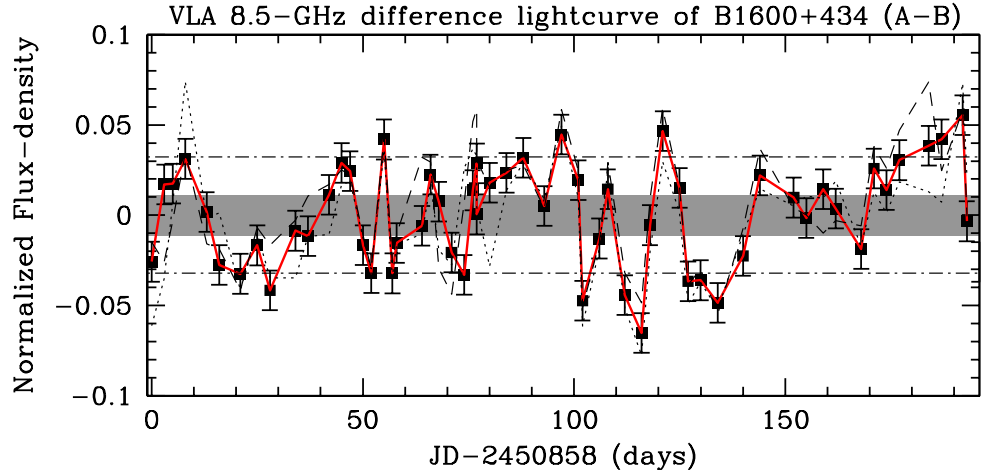


Figure 2. The normalized difference light curve between the two lens images. The shaded region indicates the expected  $1\text{-}\sigma$  (1.1%) region if all variability were due to measurement errors. The dash-dotted lines indicate the observed rms variability of 3.2%. The dotted and dashed curves indicate the normalized difference curves for a time delay of 41 and 52 days, respectively (KB99).

Let us summarize the arguments against scintillation: (i) The modulation index between the lens images differs, even though one looks at the same background source. This requires either significantly different scattering measures ( $SM_A/SM_B=3.1$ ) over a scale comparable to the image separation ( $1''.4$ ) or an image size ratio  $\Delta\theta_B/\Delta\theta_A=1.75$ , with  $\Delta\theta_A\approx 60\ \mu\text{as}$ . (ii) Ongoing multi-frequency WSRT total-flux observations ( $\gtrsim 6$  months) shows a decrease in the modulation index with wavelength ( $m_6/m_{21}\sim 2$ ), whereas the opposite trend is expected for refractive scintillation. If one would attribute all short-term variability to intrinsic source variations, it becomes very difficult to reconcile this with the fact that most short-term variability at 3.6 cm (8.5-GHz) is external and not intrinsic. The logical conclusion would be that most short-term variability seen in the WSRT 6-cm light curves is also of external origin with a modulation index smaller than that at 21 cm. (iii) A modulation index of a few percent corresponds to a variability time scale of less than 1–2 days for weak and strong refractive scattering, whereas variability over much longer scales is present.

### 3.2. Microlensing

For several reasons, microlensing is a plausible source of the external variability of B1600+434: (i) Because B1600+434 is multiply imaged, the lens images pass through a foreground lens galaxy with high microlensing optical depths, i.e.  $\tau_A\approx 0.2$  and  $\tau_B\approx 0.9$  (KB99). Combined with the fact that many core-dominated flat-spectrum radio source have superluminal jet components (Vermeulen & Cohen 1994), makes it probable that microlensing variability is occurring at some level on time scales of weeks to months. (ii) From microlensing simulations (Wambsganss 1990), we find that a static core, which does not vary

on short time scales due to microlensing (i.e.  $v_{\text{core}} \ll v_{\text{knot}}$ ), plus a single compact ( $\Delta\theta_{\text{knot}} = 2\text{--}5 \mu\text{as}$ ) superluminal ( $\beta_{\text{app}} \gtrsim 9$ ) jet component that contains 5–11% of the source flux, can explain the observed rms and time scale of variability in the lens images. For image A, however, we require an average mass of compact objects  $\gtrsim 0.5\text{--}M_{\odot}$  to explain its higher rms variability (even though  $\tau_{\text{A}} < \tau_{\text{B}}$ ). A smaller MACHO mass would result in less variability, due to the convolution of a finer magnification pattern with the source structure. (iii) The decrease in rms variability ( $m_{\lambda}$ ) with wavelength (i.e.  $m_{21} < m_6$ ), seen in the WSRT observations (Sect.3.1), is in agreement with a microlensed synchrotron self-absorbed superluminal jet component that grows proportional with wavelength, in which case one expects  $m_6/m_{21} \approx 2\text{--}3$ , comparable to the observed ratio (Sect.3.1).

#### 4. Conclusions

We have presented the first unambiguous case of external variability of an extra-galactic radio source, the CLASS gravitational lens B1600+434. Several lines of evidence point to microlensing of a superluminal jet component and not scintillation as the dominant source of this external variability. This implies the presence of a population of MACHOs in the halo around the edge-on disk galaxy with masses  $\gtrsim 0.5\text{--}M_{\odot}$ . The fact that these compact ( $\lesssim 5 \mu\text{as}$ ) structures do not seem the scintillate remains a problem to be resolved, but might be the result of the assumed simple source structure and/or the idealized mass functions of compact objects. Ongoing multi-frequency WSRT and VLA observing campaigns should further tighten the constraints on this exciting possibility to learn something about the dark matter properties at high redshifts.

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